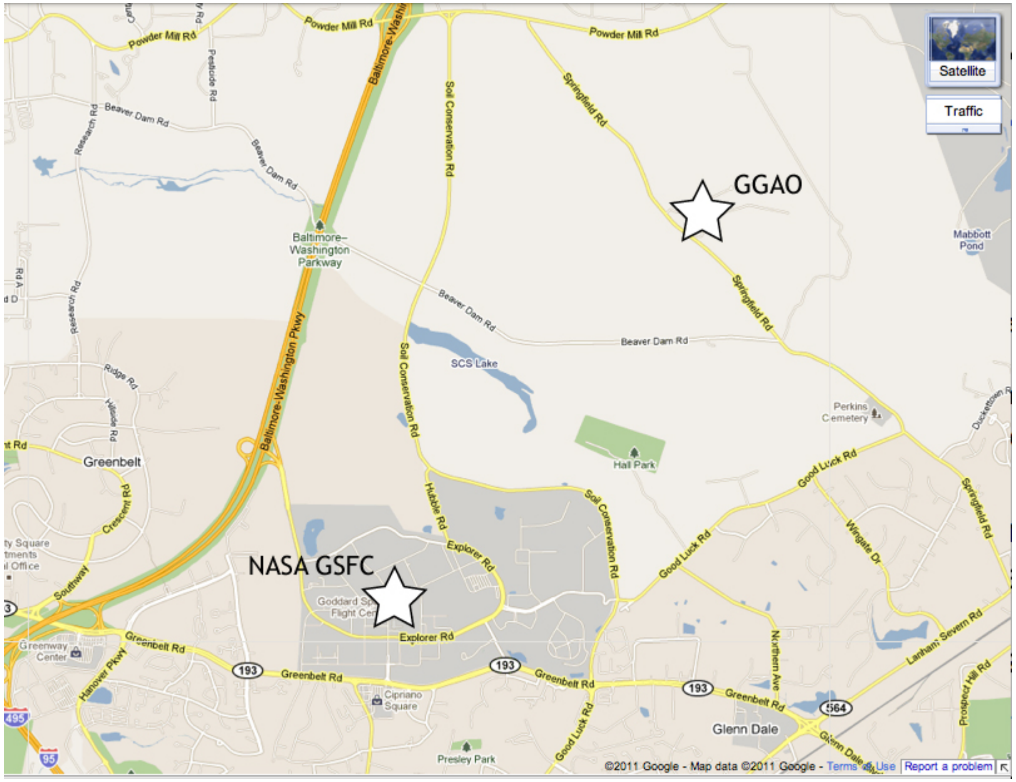
Tour of GGAO Facilities for PNT Advisory Board

Hosted by

NASA Goddard Space Flight Center

- Space geodesy overview
- User community
- NASA and space geodesy
- GGAO description

Goddard Geophysical and Astronomical Observatory (GGAO)



The Goddard Geophysical and Astronomical Observatory (GGAO) is located about 3 miles from the main campus of the Goddard Space Flight Center, in the middle of the Beltsville Agricultural Research Center. GGAO is one of only a few sites in world to have all 4 geodetic techniques co-located: Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Global Navigational Satellite System (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS).

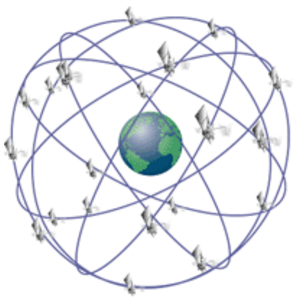
GGAO was the birthplace of SLR in 1964 when the Goddard Laser station (GODLAS) made the first successful ranges to Beacon Explorer B. There has been a continuous set of SLR measurements from GGAO since then. Currently operational SLR is performed at the MOBLAS-7 system at GGAO. This site was measured by mobile VLBI in the 1980s as part of the Crustal Dynamics Project and later by the MV-3 system mounted on a concrete pad. The next generation SLR (NGSLR) and VLBI (VLBI2010) systems are also being developed here.

Laser transponder ranging is being pioneered at the GGAO 1.2 meter telescope. The longest successful 2-way asynchronous laser ranging experiment took place between the 1.2 meter telescope at GGAO and the Mercury Laser Altimeter (MLA) onboard MESSENGER (24 Mkm) in 2005. One-way laser ranging (80 Mkm) occurred from the 1.2 meter telescope to the Mars Orbiter Laser Altimeter (MOLA) onboard MGS orbiting Mars in that same year. Multiple on-orbit calibrations of the Lunar Orbiter Laser Altimeter (LOLA) onboard LRO have taken place from the 1.2 meter telescope since LRO launched.

Many other Goddard activities are also being performed at GGAO, including operational one-way Laser Ranging to the Lunar Reconnaissance Orbiter (LRO-LR), X-Ray beam-line testing, Neutron Spectroscopy experiments, and the search for optical sources of gamma ray bursts.

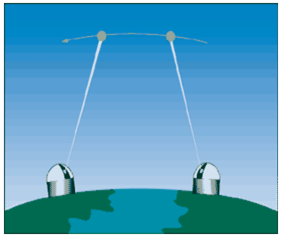
Space Geodesy (1/3)

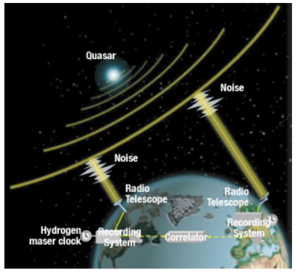
- Geodesy provides a foundation for all Earth observations
- Space geodesy is the use of precise measurements between space objects (e.g., orbiting satellites, quasars) to determine
  - Positions of points on the Earth
  - Position of the Earth’s pole
  - Earth’s gravity field and geoid



GNSS: Satellites (GPS-U.S., Russia-GLONASS, EU-Galileo) equipped with precise clocks transmitting messages such as ephemeris, clock offsets, etc. to ground (and spaced-based) receivers to measure station to satellite pseudo-range, phase delay

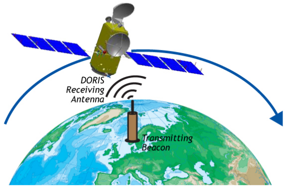
SLR/LLR: Ground-based short-pulse laser transmitting to satellites (or planetary targets) equipped with corner cubes to measure round-trip pulse time-of-flight to satellite





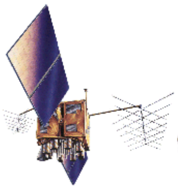
VLBI: Radio telescopes equipped with X/S wideband receivers record signals from quasars to measure difference in signal arrival times

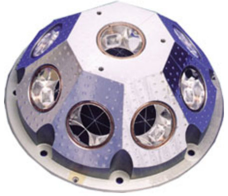
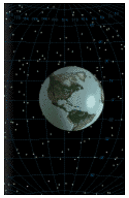
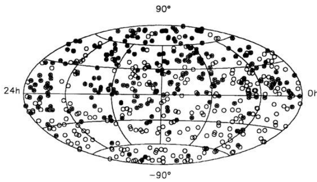
DORIS: Satellites equipped with DORIS receiver and uplink hardware transmit signals to ground beacons to measure Doppler shift on radiofrequency signals

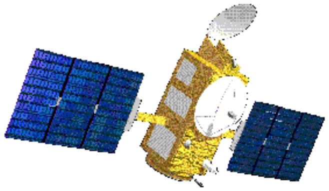


Space Geodesy (2/3)

- Data from space geodesy measurements archive are utilized for direct science observations and geodetic studies, e.g., plate motion, gravity field, earthquake displacements, Earth orientation, atmospheric angular momentum, etc.
- Data also contribute to the determination of the Terrestrial Reference Frame, an accurate set of positions and velocities
  - TRF provides the essential stable coordinate system that allows measurements to be linked over space and time; independent of the technology used to define it
  - Space geodetic networks (GNSS, SLR, VLBI, DORIS) provide the critical infrastructure necessary to develop and maintain the TRF
- Data used for Precise Orbit Determination (POD)
  - SLR and DORIS data used to calculate and verify precise orbits for Earth observation missions (e.g., ERS-1/2, ALOS, Jason-1/2, Envisat, TOPEX, etc.)
  - SLR data and GPS flight receiver data also utilized for POD efforts for other geophysical missions (e.g., GFO-1, CHAMP, GRACE, ICESat, GOCE, etc.)
- Additional products include atmosphere measurements to aid in weather forecasting, etc.
- Measurements provide critical information for accurate deep space navigation



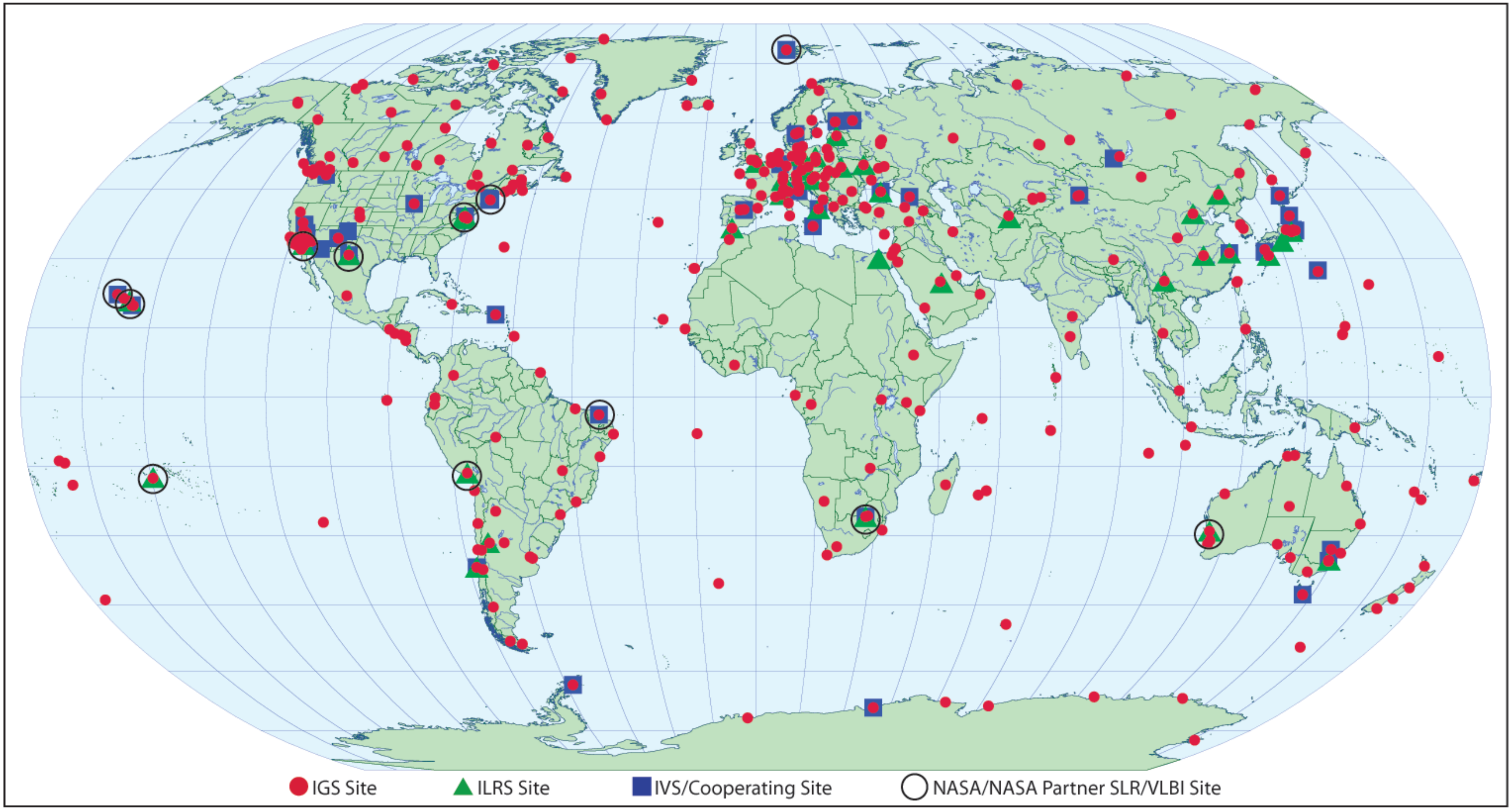








Space Geodesy (3/3)

- Data
  - GNSS: 421 sites tracking GPS, GLONASS
  - Laser Ranging (SLR and LLR): 42 sites tracking 35+ satellites (including the Moon)
  - VLBI: 39 sites
  - DORIS: 57 sites tracking 6 satellites
  - Data provided sub-hourly, hourly, daily, and multi-day basis
- Products
  - Precise network station positions (for ITRF)
  - Satellite orbits (for POD)
  - Station and satellite clocks (for timing)
  - Earth rotation parameters
  - Positions of celestial objects (for Celestial Reference Frame, CRF)
  - Atmospheric parameters (Ionosphere Total Electron Content, TEC; Troposphere Zenith Path Delay, ZPD)
  - …
  - Products provided weekly, daily, sub-daily basis

Space Geodesy: Global Networks



Scientific Contributions of Space Geodesy

- Terrestrial Reference Frame (TRF):
  - Station positions and velocities: GNSS, SLR, VLBI, DORIS
  - TRF scale and temporal variations: VLBI, SLR
  - Network densification: GNSS
  - Homogenous network distribution: DORIS
- Celestial Reference Frame: VLBI
- Precise Orbit Determination (POD):
  - Accurate satellite ephemerides: GNSS, SLR, DORIS
  - Calibration/validation for remote sensing missions, instruments: SLR, GNSS
  - Sea level monitoring: GNSS, SLR, DORIS
- Earth Orientation Parameters (EOP):
  - Polar motion and rates: VLBI, SLR, GNSS, DORIS
  - Length-of-day: GNSS, SLR, DORIS
  - UT1-UTC and long-term stability of nutation: VLBI
- Atmosphere:
  - Tropospheric zenith delays: GNSS, VLBI
  - Global maps of ionosphere mean electron content: GNSS, DORIS
  - Limb sounding for global profiles of water vapor: GNSS
- Gravity:
  - Static and time-varying coefficients of the Earth's gravity field: DORIS, SLR
  - Total Earth mass: SLR
  - Temporal variations of network origin with respect to Earth center of mass: SLR
- Timing:
  - Station and satellite clock solutions: GNSS
  - Time and frequency transfer between time laboratories: GNSS
- Fundamental Physics:
  - General relativity and alternative theories: SLR/LLR
  - Light bending, time dilation: VLBI

Who are the Users of the Data?

- International Association of Geodesy (IAG) Services
- NASA and non-NASA Flight Missions
- NSF Polar Programs
- USGS National Earthquake Hazards Reduction Program
- DoD
- Land Surveyors
- NOAA/NGS
- …

IAG Services (1/2)

- Services function as cooperating federations dedicated to a particular space geodesy technique
- Provide data and products on an operational basis to geodesy analysts as well as a broader scientific community
- Examples of a successful model of community management:
  - develop standards
  - self-regulating
  - monitor performance
  - define and deliver products using pre-determined schedules
- 200+ organizations in 80+ countries
- Successful operation through cooperation of many international organizations who leverage their respective limited resources to all levels of service functionality

IAG Services (2/2)

- NASA actively participates in the services
  - International GNSS Service (IGS)
  - International Laser Ranging Service (ILRS)
  - International VLBI Service for Geodesy and Astrometry (IVS)
  - International DORIS Service (IDS)
  - International Earth Rotation and Reference Frame Service (IERS)
- Services respond to NASA's program needs

NASA's Role Among Global Collaborators

- Networks, through the TRF, provide critical infrastructure to support flight projects
  - This support is assumed by current and future missions to be provided *yet is rarely budgeted or planned*
- NASA leverages its resources by cooperating with international partners
  - NASA supports and coordinates the geodetic services through central offices GSFC (ILRS and IVS) and at JPL (IGS)
  - This NASA coordination is a highly successful international activity endorsed by international organizations such as the IAG
  - NASA's space geodetic data sets are augmented by data contributed by other agencies to the international pool
  - These activities are supported by the Crustal Dynamics Data Information System (CDDIS), a key data center supporting the IGS, ILRS, IVS, IDS, and IERS
  - This results in access to greater and enhanced data sets and products

NASA Needs for Geodetic Networks

- Long term, systematic measurements of the Earth system require the availability of a terrestrial reference frame (TRF) that is stable over decades and independent of the technology used to define it.
- The space geodetic networks provide the *critical infrastructure* necessary to develop and maintain the TRF and the needed terrestrial and space borne technology to support the Earth science goals and missions.
- This infrastructure is composed of the:
  - Physical networks,
  - Technologies that compose them, and
  - Scientific models and model development that define a TRF

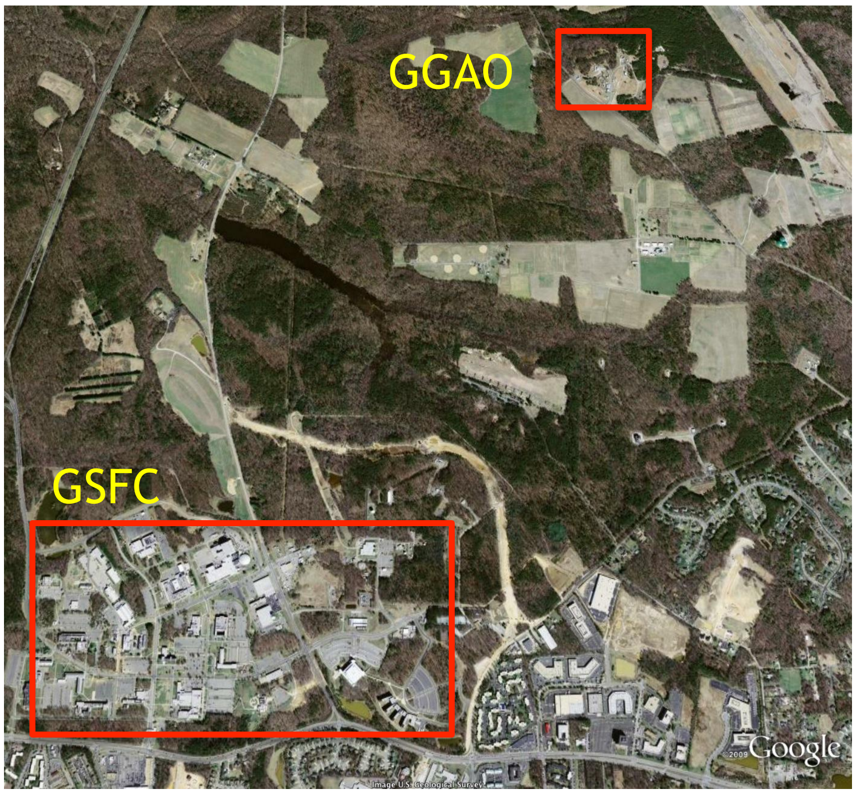
GGAO Overview (1/2)

- Goddard Geophysical and Astronomical Observatory
- GGAO is one of the few sites in the world to have all four geodetic techniques co-located at a single location: Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Global Navigational Satellite System (GNSS), and Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS)
- Code 698 is the Goddard organization responsible for VLBI, GPS and DORIS; SLR operations activity is in Code 453 with the R&D work in Code 694
- Other activities at GGAO include operational one-way laser ranging to the Lunar Reconnaissance Orbiter (694), neutron spectroscopy experiments (691), search for optical sources of gamma ray bursts (661), the X-Ray beam-line (Code 662), low frequency interferometry (Code 695), the Astronomy Club's telescope facility, and many others
- Contact Jan McGarry/694 (*Jan.McGarry@nasa.gov*) or Mike Perry/694 (*Michael.Perry@itt.com*) for more information

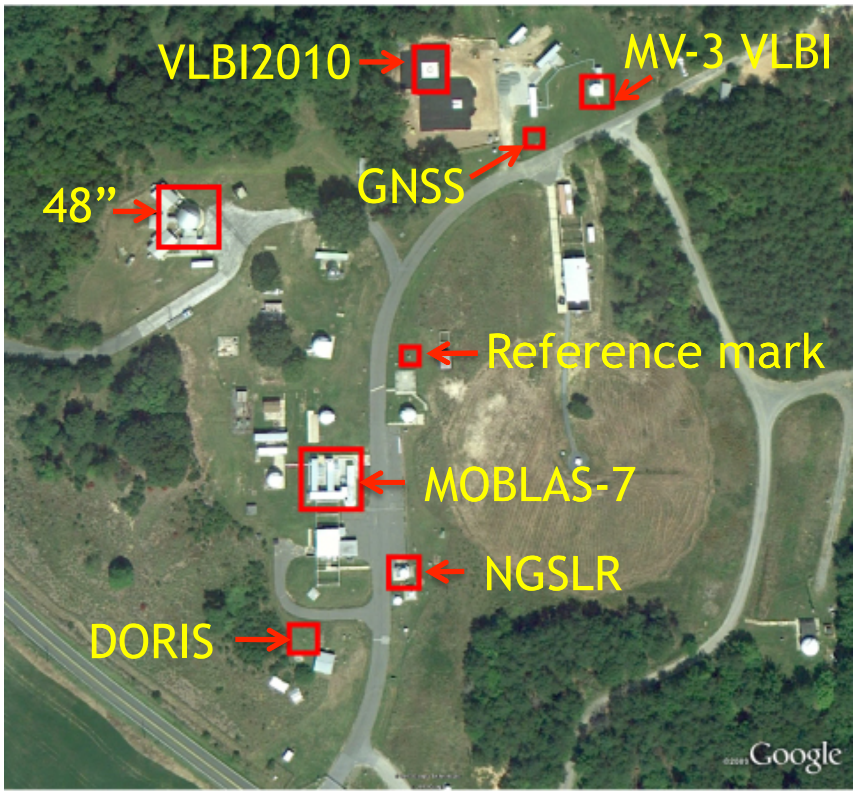
GGAO Overview (2/2)

- GGAO is located 3 miles from Goddard, on Springfield Road, in the middle of the Beltsville Agricultural Research Center
- *http://cddis.gsfc.nasa.gov/ggao*

Local Area Map

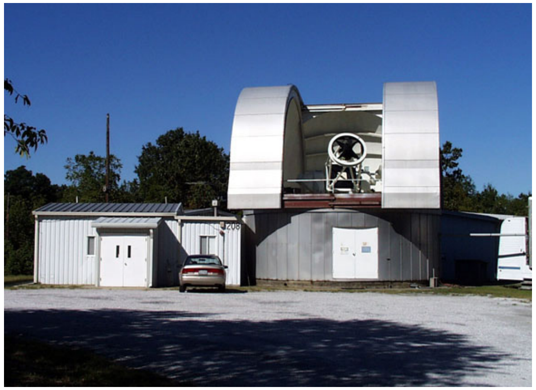


GGAO



SLR at GGAO

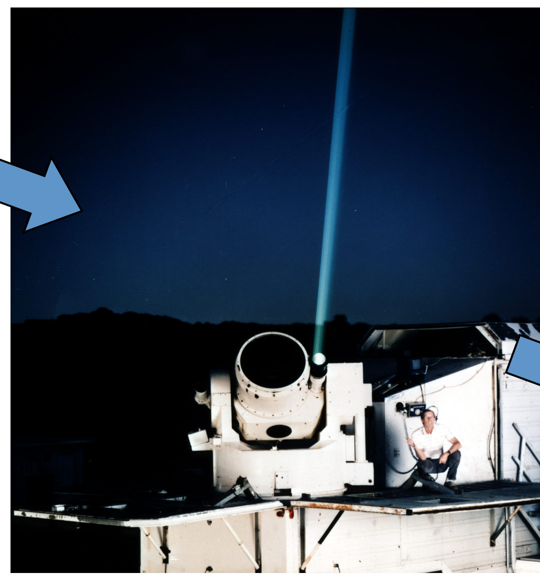
- GGAO is home to NASA's SLR activities. Developed at Goddard in the early 1960's as a very accurate tracking technique for satellites carrying retro-reflectors, SLR is now practiced in over 30 countries
- Two SLR stations at GGAO, MOBLAS-7 and NGSLR, support the laser ranging activities of the International Laser Ranging Service (ILRS), *http://ilrs.gsfc.nasa.gov*; the 1.2M telescope performs R&D activities
- "NGSLR (NASA's Next Generation SLR) has been performing one way (uplink only) ranging to the Lunar Reconnaissance Orbiter (LRO) for the last ~ 2 years, providing 10 cm accurate ranges used in the determination of onboard clock drift and aging, and eventually for use in more precise orbit determination
- The 1.2 meter telescope is performing periodic on-orbit calibrations of the Lunar Orbiter Laser Altimeter (LOLA) onboard LRO; three successful on-orbit calibrations have been performed so far
- <u>Reference & citation</u>:
  Pearlman, M.R., Degnan, J.J., and Bosworth, J.M., The International Laser Ranging Service, *Adv. Space Res.* , 30(2), pp. 135-143, 2002. DOI:10.1016/S0273-1177(02)00277-6.



SLR at GGAO: Past, Present, Future

- GGAO is home to NASA's SLR activities. Developed at Goddard in the early 1960's as a very accurate tracking technique for satellites carrying retro-reflectors, SLR is now practiced in over 30 countries.
- Continuous set of GGAO SLR data since 1964

Past: GODLAS



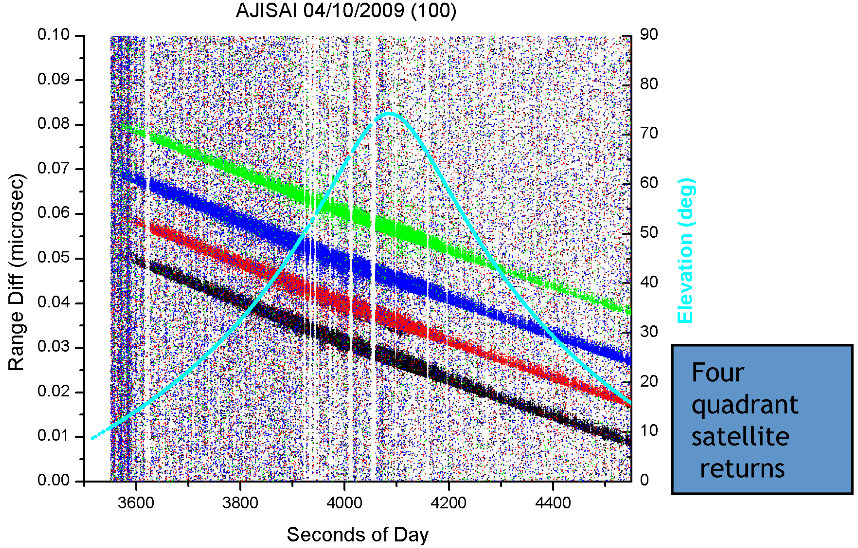
Present: MOBLAS-7

Future: Next Generation Satellite Laser Ranging (NGSLR)

NGSLR Development at GGAO

NASA's Next Generation Satellite Laser Ranging System (NGSLR) is a low energy/high repetition rate singe photon detection laser ranging system capable of tracking cube corner equipped satellites in earth orbit. The concept of NGSLR was developed by J. Degnan (GSFC, retired) in the 1990s. Technical development continues in code 694. The system has demonstrated tracking of earth orbit satellites with altitudes from ~ 1000 km to 20000 km. Completion of the NGSLR prototype will occur during the Space Geodesy Proposal period.

OMC ranging plot of satellite returns



- System Features:
  - 1 to 2 arcsecond pointing/tracking accuracy
  - Track CCR equipped satellites to 20,000 km altitude, 24/7 operation
  - Reduced ocular, chemical, electrical hazards
  - Semi automated tracking features
  - Small, compact, low maintenance, increased reliability
  - Lower operating/replication costs

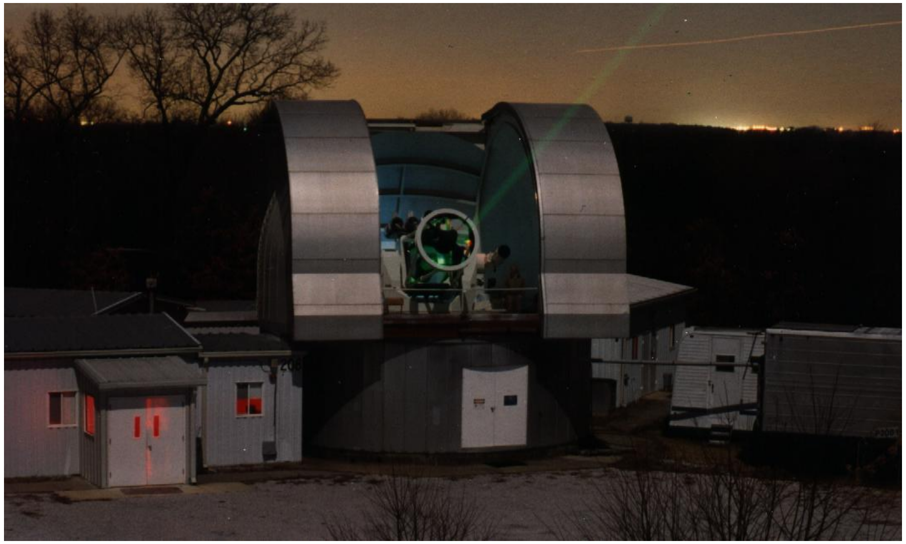
LRO-LR at GGAO

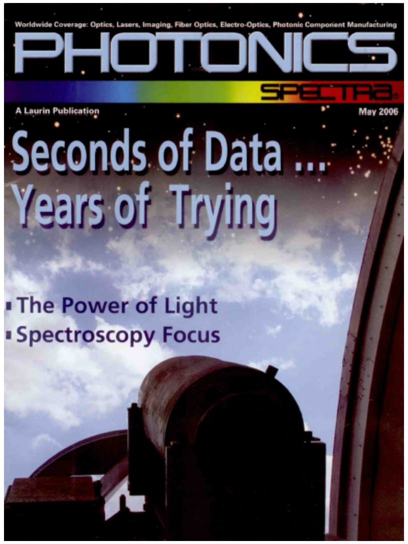
- Laser Ranging (LR) to LRO from NGSLR operationally 7 days a week.
- LR is 1-way laser uplink. Feedback via LOLA housekeeping data in semi-real-time.
- LR provides drift and aging of the LRO onboard oscillator and will eventually be used for precision orbit determination.
- Over 480 hours of ranging data from NGSLR to LRO since launch (June 2009)

- <u>Reference & Citation</u>:

  M.T. Zuber, D.E. Smith, R.S. Zellar, G.A. Neumann, X. Sun, J. Connelly, A. Matuszeski, J.F. McGarry, et al,"The Lunar Reconnaissance Orbiter Laser Ranging Investigation", Volume 150, Numbers 1-4, January.

48"(1.2 Meter) Telescope Facility at GGAO





- Multi-user facility built in 1973-74
- Arc-second precision tracking telescope
- Has supported many GSFC experiments including:
  - Mercury Laser Altimeter (MLA) Earthlink 2-Way Laser Ranging
  - MLA onboard MESSENGER at distance of 24 Mkm (Smith, Zuber, Sun, Neumann, Zagwodzki, McGarry): May 2005
  - Mars Orbiter Laser Altimeter (MOLA) Earthlink 1-Way Laser Ranging.
  - MOLA onboard MGS orbiting Mars at ~80 Mkm (Smith, Abshire, Sun, Zuber, Neumann, Zagwodzki, McGarry): Sep 2005
  - LOLA on-orbit calibration, 2-way laser ranging (Smith, Zuber, Zagwodzki, McGarry, Sun, Liiva, Neumann): Aug & Sep 2009

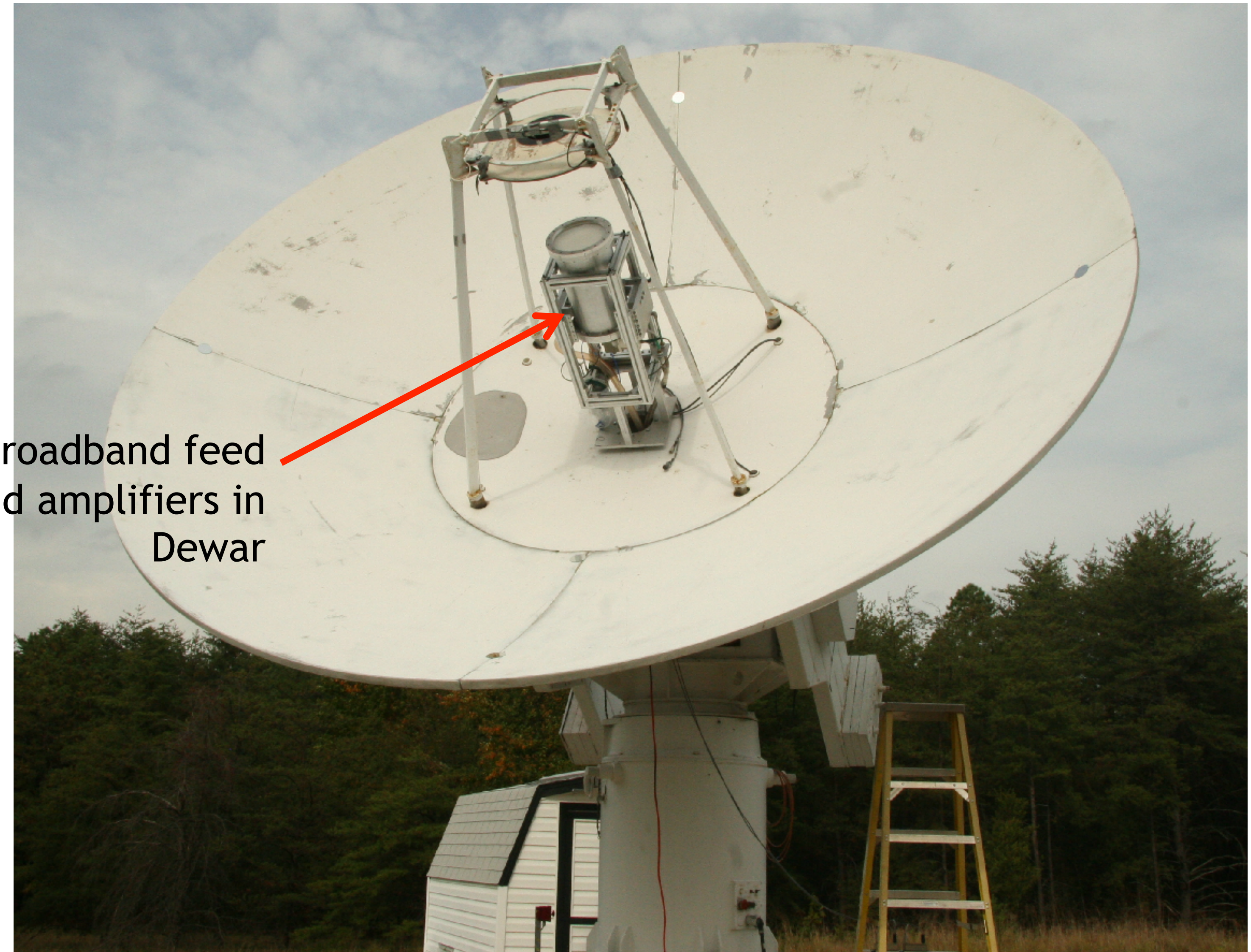
VLBI at GGAO

- MV-3 system was originally a mobile VLBI station supporting the Crustal Dynamics Project that began in 1980
- Mobile system made measurements in western U.S., Alaska, and Europe.
- Since 1993, MV-3 has been a fixed site at GGAO and part of the global network supporting the International VLBI Service for Geodesy and Astrometry (IVS), *http://ivscc.gsfc.nasa.gov*
- MV-3 now serving as a testbed facility for NASA VLBI R&D, including VLBI2010 development
- Reference & Citation:
  W. Schlüter, D. Behrend, The International VLBI Service for Geodesy and Astrometry (IVS): current capabilities and future prospects, *J Geod*, 81(6–8), pp. 379–387, 2007. DOI: 10.1007/s00190-006-0131-z

VLBI2010 Accomplishments to Date

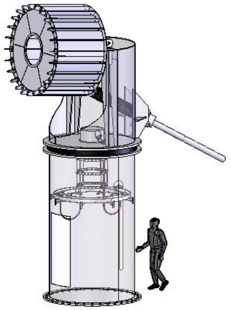
- Mount cryogenic broadband feeds on antennas at Westford, MA and GGAO
  - Record 512 MHz from 4 bands between 2 GHz and 14 GHz
  - Dual linear polarizations
- Down convert each band using flexible Up-Down Converter (UDC)
- Separate each band into 32 MHz channels using Digital Backend (DBE)
- Record 2 Gbps on each of 4 Mk5B^{+} recorders
- Install fast 12-m Patriot antenna to significantly increase observations
- VLBI2010 data expected to be phase delay with much lower uncertainty than current group delay observable
- Entire VLBI2010 system is newly designed. Some currently deployed equipment dates from the 1970s

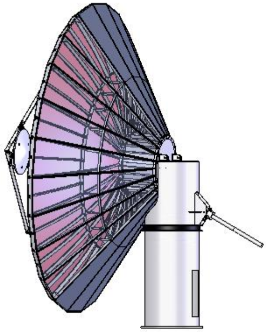
MV-3 5-Meter Antenna



Patriot 12-Meter VLBI Antenna

- Erected at GGAO October 2010
- Quad Ridge Feed Horn (QRFH) designed by Caltech for Patriot optics being tested





GNSS at GGAO

- Two GNSS receivers (GPS and GPS+GLONASS) share a common antenna at GGAO
- Both receivers are key contributors to the International GNSS Service (IGS), *http://igscb.jpl.nasa.gov*
- JPL provides installation and infrastructure support for receiver, antenna, and data download
- GGAO also used for engineering tests of various GNSS antennas
- <u>Reference & Citation</u>:

  Dow, J.M., Neilan, R. E., and Rizos, C., The International GNSS Service in a changing landscape of Global Navigation Satellite Systems, Journal of Geodesy (2009) 83:191–198, DOI: 10.1007/s00190-008-0300-3

DORIS at GGAO

DORIS Global Network

- GGAO DORIS beacon part of a global network of ~57 stations
- DORIS@GGAO since June 2000
- Beacons emit at 2 Ghz and 400 Mhz; the observable is dual-frequency 1-way Doppler
- DORIS receivers are located on altimeter (TOPEX/Poseidon, Jason, ENVISAT) and remote sensing (SPOT) satellites; future satellites include: Cryosat-2, Jason-3, SWOT & SENTINEL-3
- DORIS data are used for Precision Orbit Determination, and contribute to IERS reference frame realizations
- International DORIS Service URL: *http://ids.cls.fr*
- <u>Reference & Citation</u>: Tavernier, G., Fagard, H., Feissel-Vernier, M., et al., The International DORIS Service: Genesis and early achievements, *J. Geod. 80(8-11)*, pp. 403-417, 2006. DOI: 10.1007/s00190-006-0082-4.

Co-Location Monitoring

- Automated measurement of inter-instrument vectors is an essential aspect of an integrated space geodesy station
- Measurements provide closure between terrestrial reference frames derived from different space geodesy techniques
- Tests of technologies and currently available systems underway at GGAO